



Acquisition and Evaluation of Time- Variant Drawdown Datasets for Borehole Efficiency and Groundwater Prospect - A Case Study

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Abstract: Acquisition and evaluation of the time – variant drawdown datasets was undertaken in shallow boreholes in parts of the Fadama Floodplain of river Jama'are in the West Chad Basin Northeastern Nigeria. The objectives of the study included the evaluation of borehole efficiency, hydrogeological boundaries and properties of aquifers for the assessment of groundwater conditions and prospect in the area. The step-drawdown/variable and constant rate tests were conducted on 41 boreholes with two-time dependent cycles - drawdown and recovery using a high capacity pump SP27-11 rated 7.5 Hp. The electrical depth sounder measuring device was used to determine changes in drawdown and the static water levels in boreholes. Results showed three groundwater conditions; intermittent recharge (18.2 %), casing storage (24.2 %) and recharge conditions most predominant of all the drawdown type-curves with 57.5% occurrence. The yields of boreholes ranged between 2.0 and 13.4 litre/sec (172.8 and 1163.81 m³/day), while the specific capacity values varied from 52.1 - 756.0 m³/day/m with entrance velocity and well efficiency values of between 0.0048 to 0.0075 m/s and 19.1 to 94.9 % respectively. It may therefore, be concluded that the recharge source and well efficiency were of higher percents in the overall assessment as indicators to good groundwater prospect and well design practices. This is evident from the range of transmissivity and hydraulic conductivity values of 113.2 - 1436.6 m²/day and 6.67-101.31 m/day respectively. Other hydrogeological characteristics such as specific capacity and entrance velocity values also suggested a zone of good infiltration coefficient, hydraulic conductivity and propensity for high groundwater yield supplies of boreholes in the area.

Keywords: Evaluation, efficiency, floodplain, capacity, drawdown, groundwater

I. Introduction

A case study of interest present in this study is the River Jama'are floodplain water resources in Northeastern region in Nigeria. It constitutes one of the main groundwater provinces of Katagun areas in Bauchi state (FSN, 1978) and lies solely within the western part of the Nigerian portion of the Chad Basin - west of Komadugu (Fig. 1). The area has a peculiar hydrogeological characteristics arising from its location within the sedimentary-basement transition zone (GSN, 1978). The sedimentary sequence is characterized by a complex variation of facies changes that rapidly thins out towards the basement complex rocks' boundary (Carter *et al.*, 1963; Matheis, 1989). More than 95% Jama'are and Azare water supply systems for domestic and agriculture uses come from groundwater either from wells or springs (BSADP, 1988; BSWB, 2000; NWRP, 2000; Mohammed, 2007). Generally speaking, the main problems facing water resources in developing countries include but not limited to water level decline caused by groundwater over-pumping (uncontrolled pumping) from production wells, cluster of wells in specific area, and drought conditions that minimize recharge of aquifers/wells (Offodile, 1992; Deeb, 2005; Mohammed, 2015)

Time – variant drawdown analysis essentially goes with the goal of determining flow rates, drawdown level and unforeseen factors used for the estimation/analysis of aquifer parameters and well operational characteristics to avert problems facing water resources. Also from the analysis, hydrogeological properties of aquifers and their significance may be measured for the overall sustainability for high capacity and dependable long-term groundwater conditions or resource development, utilization and maintenance programmes in the area (Mohammed, 2007).

A pumping test is designed to cause the disturbance of natural groundwater flow when a borehole is pumped under controlled conditions so as to analyze its effects (CAT, 2003; Mohammed, 2007). Pumping tests method involving standard instrumental tests of time – variant drawdown - the variable rate step-drawdown and constant discharge rate was employed in the present study. The tests, otherwise called time-drawdown tests, are non steady-state tests and consist of pumping a well at a certain rate and measuring/recording the drawdown observed at specific times. These tests were conducted at boreholes in this study with two-time dependent cycles (drawdown and recovery).

The variable rate step-drawdown test has been developed to examine the performance of wells having turbulent flow (Jacob, 1946 a & b). The test is usually commenced after well development when the static water level would have recovered. Recovery data may be obtained to verify the accuracy of the pumping data. Qualitative analysis of drawdown of the constant discharge rate data is undertaken to identify or conceptualize groundwater flow regimes strictly on the basis of curve shape during each pumping test, and may also be exploited to identify hydrogeological conditions that are likely to affect drawdown responses (Mohammed, 2007). Such hydrogeological conditions as casing storage and boundary effects are diagnosed on comparing the field drawdown responses to the Theis and Jacob model responses. The quantitative analysis of the constant rate involves the application of analytical model to each drawdown-time response (early, middle and late) with a view to providing estimates of the hydraulic parameters and other well characteristics/relationships while the analysis of the variable rate step-drawdown involves the determination of the specific/production capacity and yield/well efficiency (Driscoll, 1986; CAT, 2003; Mohammed, 2007). These relationships are used to help in the evaluation of borehole efficiencies, designing of the production pumps, evaluate well development/performance and determining well maintenance programmes, and any other limiting factors, if any, to ameliorate borehole failure and prolong borehole life.

II. The Basic Equations and Analytical Techniques

Assuming that the well is fully developed and efficient with laminar flow conditions, that no near turbulent flow losses occurs, the drawdown in a pumping well satisfies this expression (Jacob, 1946 b; Driscoll, 1986):

$$S_w = BQ \quad (1)$$

Where, S_w = total drawdown in the borehole in metres, Q = discharge rate of the borehole in m^3/day , $B = 264/T \cdot \log(0.3 Tt/r^2S)$, and its time dependent, it is expressed as coefficient of formation loss due to laminar flow in the formation in metres.

Conversely, the ultimate drawdown in a well measured at the designed rate Q of continuous pumping for a given period was different from that obtained from the Eq. (1) due to well losses. The total drawdown (S_w) was made up of: (i) head loss resulting from laminar flow in the formation (formation loss), (ii) head loss resulting from the turbulent flow in the zone close to the well face, (iii) head loss through the well screen, (iv) head loss in the well casing. The total drawdown (S_w) can be more accurately expressed as the sum of a first-order (laminar) component and a second-order (turbulent) component (Jacob, 1946). Eq. (1) thus becomes:

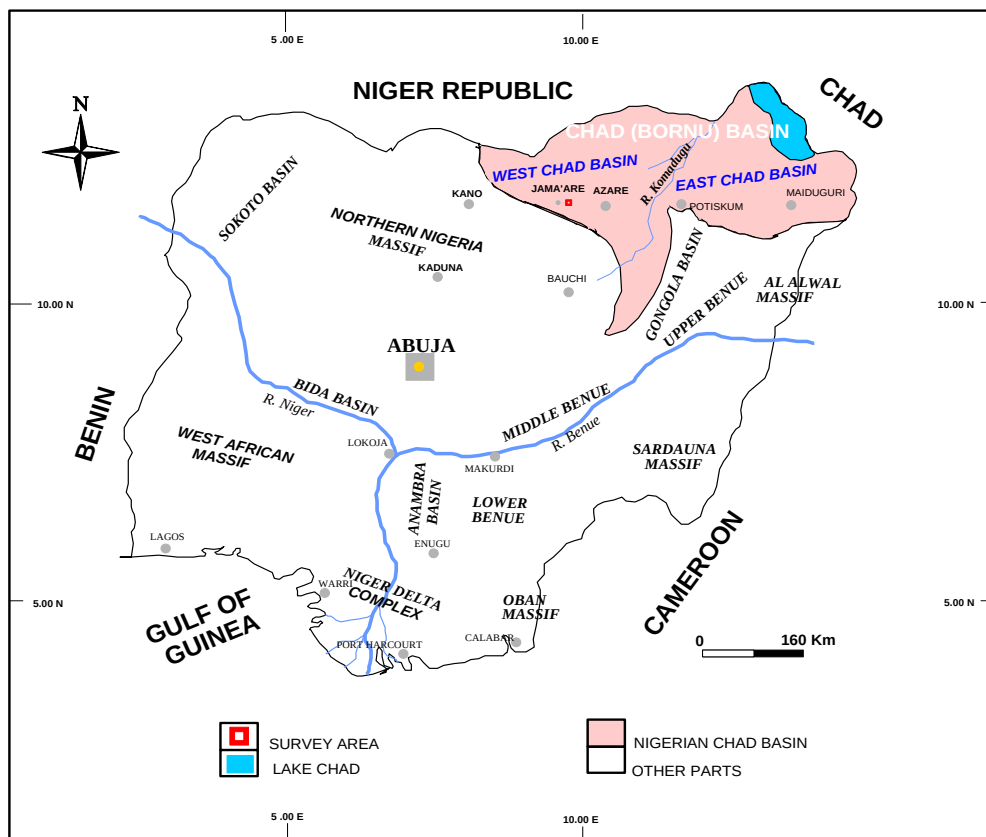


Figure 1: Map of Nigeria showing the extend of the Nigerian Chad Basin

$$S_w = BQ + CQ^2 \quad (2)$$

$$\text{and, } \frac{S_w}{Q} = B + CQ \quad (3)$$

where, BQ = the laminar term (the formation/aquifer loss), expressed in metres, and defined as the drawdown caused by resistance to laminar flow in the aquifer.

CQ^2 = the turbulent term (the well loss or head loss attributable to inefficiency), expressed in metres, and defined as the drawdown or head required to overcome resistance to turbulent flow in the borehole, through the screen and up the borehole, B = coefficient of formation loss due to (i) above, in metres; and C = coefficient of well losses due to (ii), (iii) and (iv) above, in metres (Walton, 1962; Raghunath, 1979) and are constant coefficients. S_w / Q = specific drawdown (reciprocal of specific capacity). Therefore, the approach adopted in analyzing the variable rate step-drawdown test data was to evaluate Eq. (1) or Eq. (2).

The above equation is most useful in evaluating the magnitude of turbulent head loss for the purpose of determining optimum pumping rates, well efficiency, specific drawdown of the well at various discharge rates, and may equally be used to determine the transmissivity values of aquifer from the time-drawdown graphs plotted for one of the constant rate steps of the step test. The efficiencies of the boreholes may be calculated from the relation:

$$\text{Well efficiency (E)} = BQ/S_w \times 100 \quad (4)$$

The Constant-discharge rate test analysis remains a valuable suite or tool in groundwater studies and modeling (Mohammed, 2007). The analysis of the time-drawdown curves enabled both the qualitative and quantitative evaluation of the transmissivity, hydraulic properties, specific capacity, future drawdown of the well and aquifer system as shown from the following empirical relationships:

(a) Transmissivity (T): This describes how transmissive an aquifer is in moving water through pore spaces (Driscoll, 1986). It is a product of hydraulic conductivity and the saturated thickness and defined as the rate of flow moving through the entire saturated thickness of an aquifer having a width of 1 m under hydraulic gradient of 1 (100 percent). Transmissivity (T) values of water-bearing formations are estimated from the pumping (field) test data and the geoelectric parameters using the Cooper and Jacob (1946) and Maillet (1947)/Niwas and Singhai (1981) modified equations respectively. Transmissivity is thus expressed as:

$$T = Kb \quad (5 a)$$

Where b = average saturated thickness/screen length in metre, and K = hydraulic conductivity in m^2/day ,

$$T = \frac{2.3Q}{4\pi\Delta s} \quad (5 b)$$

or

$$T = \frac{0.183Q}{\Delta s} \quad (5 c)$$

Where, T = coefficient of transmissivity in m^2/day , Q = Pumping rate in m^3/day , Δs = change in drawdown between two log cycles or change in drawdown between 10 and 100 minutes after the start of the pumping test (i.e. $S_{w100} - S_{w10}$) in metre.

(b) Hydraulic conductivity: Hydraulic conductivity (K) is expressed as flow rate in m^2/day through a cross-section of the aquifer under a hydraulic gradient of 1

$$K = \frac{T}{b} \quad (6)$$

Hydraulic conductivity varies widely for unconsolidated porous materials, being high for sands and gravels and low for silts and clays with low effective porosity.

(c) Specific capacity: Specific capacity (q) is defined as

$$q = \frac{Q}{s} \quad (7)$$

Where, q = specific capacity in $m^3/\text{day}/m$, Q = discharge rate, in m^3/day , s = drawdown at end of test, in m

(d) Expected Drawdown Estimation: Expected drawdown at specific discharge rate can be estimated from Eqs. (5 b and c) above. In addition, the time-drawdown graphs provide graphical means of predicting future drawdown(s). The straight lines in the time-drawdown graphs were extrapolated to the right to indicate the expected drawdown after longer periods of pumping at the same rate.

(e) Entrance Velocity Through Screens: Entrance velocity at pumping rate of the borehole may be evaluated to enable a reassessment of the well design practices.

The general equation relevant for the estimation of the entrance velocity is given as:

$$V = \frac{Q}{\pi d l p} \quad (8)$$

or

$$V = \frac{Q}{A_t} \quad (9)$$

where, V = entrance velocity in m/s, Q = envisaged discharge rate in m^3/day , d = diameter of screen in metre, l = length of screen in metre, p = percentage of opening in screen, A_t = open area of the total length of screen in metre. The calculated entrance velocity for good well design would lie within the upper limit of 0.03 m/s recommended by American Water Works Association (AWWA) (Driscoll, 1986; Roscoe, 1990). The transmitting capacity of the screen (T_m) may also be estimated by multiplying the open area by a factor of 0.031 (Driscoll, 1986). The estimates from the relationships deduced above remain as tools to unearth relevant information on well and aquifer characteristics.

III. Method of Study

A. Acquisition of Pumping Test Data

The step drawdown and constant rates were the two pumping datasets acquired. Figure 2 shows spatial distribution of a total of 43 boreholes drilled (41 production, 1 observation and 1 test boreholes) in the study area. The step drawdown measurements were initially carried out by pumping boreholes individually at four successively higher pumping rates and durations (Q_1 , Q_2 , Q_3 , and Q_4) using a high capacity pump (up to 10 l/s) rated SP27-11 (7.5 Hp) and the drawdown (water level in the pumping wells) for each rate, or step, was continuously recorded until the drawdown stabilized. As this was achieved, the power was shut down and the pumping action halted to allow the water level in the boreholes to start to recover to its static water level. Recovery data were also taken and recorded at the instant the pumping action was stopped. The changes in drawdown and the static water levels in boreholes during both stages were determined by a measuring device called electrical depth sounder.

The constant-discharge rate datasets were acquired in turn using the same well operational set-ups as the variable rate step-drawdown except that the wells were pumped and maintained for a significant length of time of 72 hours (3 days) at a maximum for a constant discharge rate (Q) litres per seconds for each of the wells. Such long-term pumping may reveal the presence of near hydrogeological boundaries affecting wells operation. The drawdown which resulted as constant amount of discharge was continuously taken out of wells was continuously observed and recorded until the drawdown was stabilized. Discharge readings were periodically checked and recorded for any variation in the pump/discharge rates. The recovery data were also recorded in the same frequency as those obtained during the pumping sections of the test.

B. Analyses of Pumping Test Results

Analysis of pumping test data requires an appreciation of all factors that can affect the drawdown data. The analysis visualizes the physical nature of the aquifer and how it deviates from the basic assumptions on which well hydraulic equation are based. The results of the qualitative/quantitative analysis of the drawdown data are presented as drawdown curves, graph and tables.

From the variable rate step drawdown test data bank, graphs of drawdown against pumping time were plotted on a semi logarithmic graph paper using an interactive computer software algorithm called Microcal Origin developed in South Korea (Fig. 3). The drawdown during each step of the variable (step) test was extrapolated, and used to determine the incremental drawdown (s_n), caused by a change in the pumping rate. The sum of the incremental or cumulative drawdown ($s = \sum s_n$) for each step was determined, from which values of specific drawdown were estimated and subsequently recorded (Table 1). The specific drawdown (s_w/Q) values were plotted against the discharge rates (Q) on a linear scale. A straight line graph whose interception at the ordinate of the plot (that is, specific drawdown s_w/Q axis) gives the aquifer loss coefficient 'B' and the slope gives the well loss coefficient 'C'. The coefficients B and C were determined by a simple graphical or mathematical method of analysis similar to those adopted by earlier workers (Cooper and Jacob, 1946; Bierschenk, 1964; Driscoll, 1986; Roscoe, 1990). These were used for quantitative estimate of well efficiency and other hydraulic/well parameters. The transmissivity and hydraulic conductivity were obtained from the slopes (Δs) of the first and second legs of the constant discharge time drawdown curves.

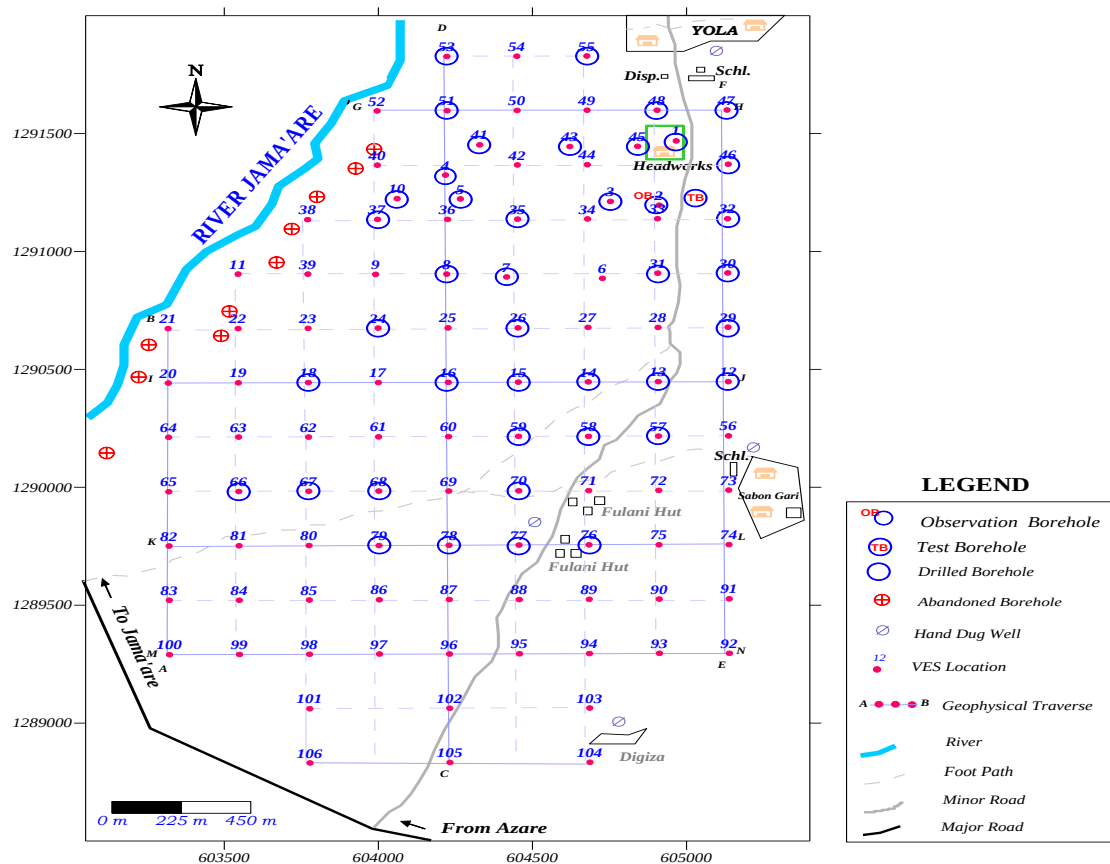


Fig. 2. Map showing the location of boreholes

IV. Results and Discussion

A. Results

The results from the variable rate step drawdown analysis are shown as borehole efficiencies, specific drawdowns, aquifer and well loss coefficients while the constant discharge rate pumping test analysis results are shown as borehole yields, hydraulic parameters, hydrogeological boundaries/conditions (the recharge source and steepening/casing storage effects) while.

B. Discussion

Table 2 below shows the estimated values of specific capacity, borehole efficiency, hydraulic parameters and borehole yields and other characteristics. The specific capacity values vary from 52.1 - 756.0 m³/day/m with borehole/well efficiency of 19.1 - 94.9 % respectively. The transmissivity (T) values recorded vary from 122.7 - 10427.5 m²/day while the hydraulic conductivity (K) values vary from 6.7 - 1329.4 m/day. The typical specific drawdown curve in Fig. 4 gives value of formation and well loss coefficients, and similar curves peculiar to other boreholes give respective values of these quantities. The entrance velocity values of between 0.0048 - 0.0075 m/s. The borehole yields at a shallow depth (10 - 25 m) range between 9.0 and 13.4 litre/sec (779.3 and 1163.81 m³/day) while the yields range for few deep depth boreholes is between 2.0 litre/sec (172.8 m³/day) and 6.9 litre/sec (602.2 m³/day). The consistent decrease observed in borehole yields with depth is not unexpected considering the scale of occurrence of alluvium vis-à-vis the underlying thick and clayey Chad Formation/weathered basement unit (Mohammed and Olorunfemi, 2012). Yields diminish at deep depths below the alluvium unit due to the too clayey matrix of the Chad formation which grades into the weathered basement zone with consequent low permeability. Groundwater yields in the basin, therefore, generally decrease with increase in borehole depth (Mohammed and Olorunfemi, 2012).

A condition of no recharge or intermittent recharge, recharge source and steepening/aquifer casing storage effects are the three distinct hydrogeological features or geological anomalies within the radius of influence of the productive/yielding boreholes in the basin (Figs. 5 - 7). The delineation of these features arise from the dispositional pattern/shape of the constant discharge rate time-drawdown type-curve from visual inspection of the curves relationships. The extension of the time-drawdown curves to the left shows predicted drawdown values of between 1.75 and 9.6 m. The significantly high values of some of the drawdowns recorded correspond to drawdowns in areas away from the recharge source; while diminutive drawdown values indicate a better

recharge tendency for wells nearer the recharge source after 1440 minutes of the same period of continuous pumping.

Fig. 5 is a typical time-drawdown curve for pumped wells operating under condition of no recharge or intermittent recharge as assumed by Jacob model assumptions. The pumping level in wells goes down consistently as pumping continues between constant discharge rates of 864 and 1144 m³/day for a period of three (3) days. About 18.2 % of the total curves represent this class of well performance. The future drawdowns in these wells for any longer period of continuous pumping at specific discharge rates were estimated by extrapolation of the straight line to the right. The values obtained vary from 1.39-8.75 m, which are significantly enough to suggest that at longer pumping the type-curves may support a continuous pumping.

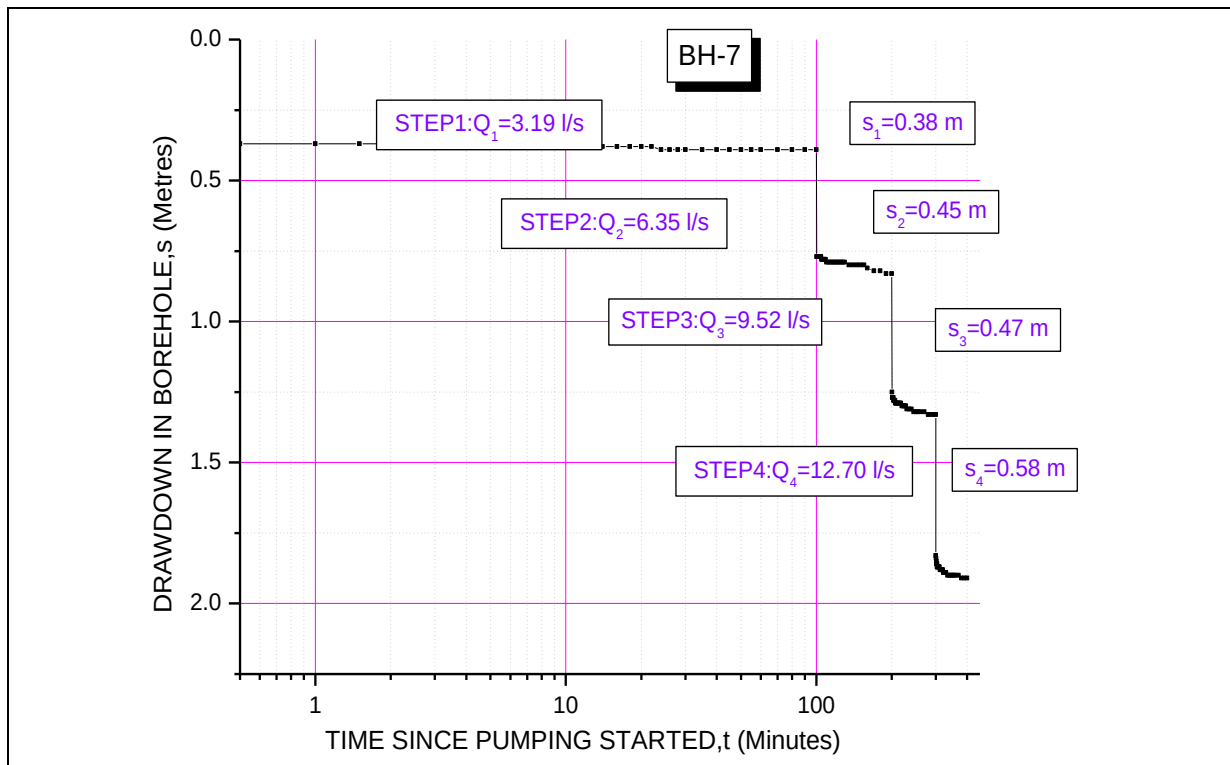


**Fig. 3: Typical variable rate step-drawdown curves
(for t =100 min after the start of each step)**

Table 1: Step-drawdown test data for borehole-BH 7

Step	Discharge Rate (Q)	Incremental Drawdown (s_n)	Cumulative Drawdown $s = \sum s_n$	Specific Drawdown s/Q
(n)	(l/s) : (m ³ /day)	(m)	(m)	(m/m ³ /day)
1	3.19 : 275.62	0.38	0.38	0.001379
2	6.35 : 551.23	0.45	0.83	0.001506
3	9.52 : 822.53	0.47	1.3	0.001580
4	12.70 : 1097.28	0.575	1.875	0.001713

Table 2. Some results of values from the analysis

Borehole	Borehole capacity Length (m)	Specific T (m ² /day/m)	Aquifer Efficiency (m ² /day)	Aquifer K (%)	Borehole Code Yield (m/day)	Screen (m ³ /day)
BH- 7	14.21	543.21	2008.02	76.2	141.31	1097.28
BH-13	19.97	201.87	354.9	62.6	17.17	1086.05
BH-14	16.95	403.74	893.33	87.2	25.70	1073.95
BH-15	14.16	114.29	374.82	78.7	26.47	1044.58
BH-16	14.15	115.29	254.72	50.7	17.36	1141.34
BH-18	14.25	189.85	380.91	95.8	26.73	1144.8
BH-26	14.16	118.69	552.08	65.2	38.99	1086.05
BH-29	14.16	202.24	1046.04	80.8	73.87	1086.05
BH-30	14.16	152.99	375.59	76.5	26.52	1087.73

BH-41	19.88	109.67	525.62	78.9	26.44	1062.72
BH-43	19.88	216.49	958.01	82.3	48.19	1151.71
BH-57	16.98	99.2	113.24	31.3	6.67	1144.8
BH-59	14.13	417.29	810.63	87.3	57.37	1151.71
BH-67	14.15	222.49	78.67	73.3	78.65	1094.69
BH-68	14.15	83.68	585.94	19.1	41.41	1088.64
BH-70	14.14	218.49	1005.59	47.5	71.12	1099.01
BH-76	14.16	160.95	506.77	86.3	35.81	1080
BH-77	14.25	467.12	637.24	85.8	44.72	1062.12
BH-78	14.12	274.67	755.89	84.1	53.53	1073.95

Note: Transmissivity and K = Hydraulic Conductivity

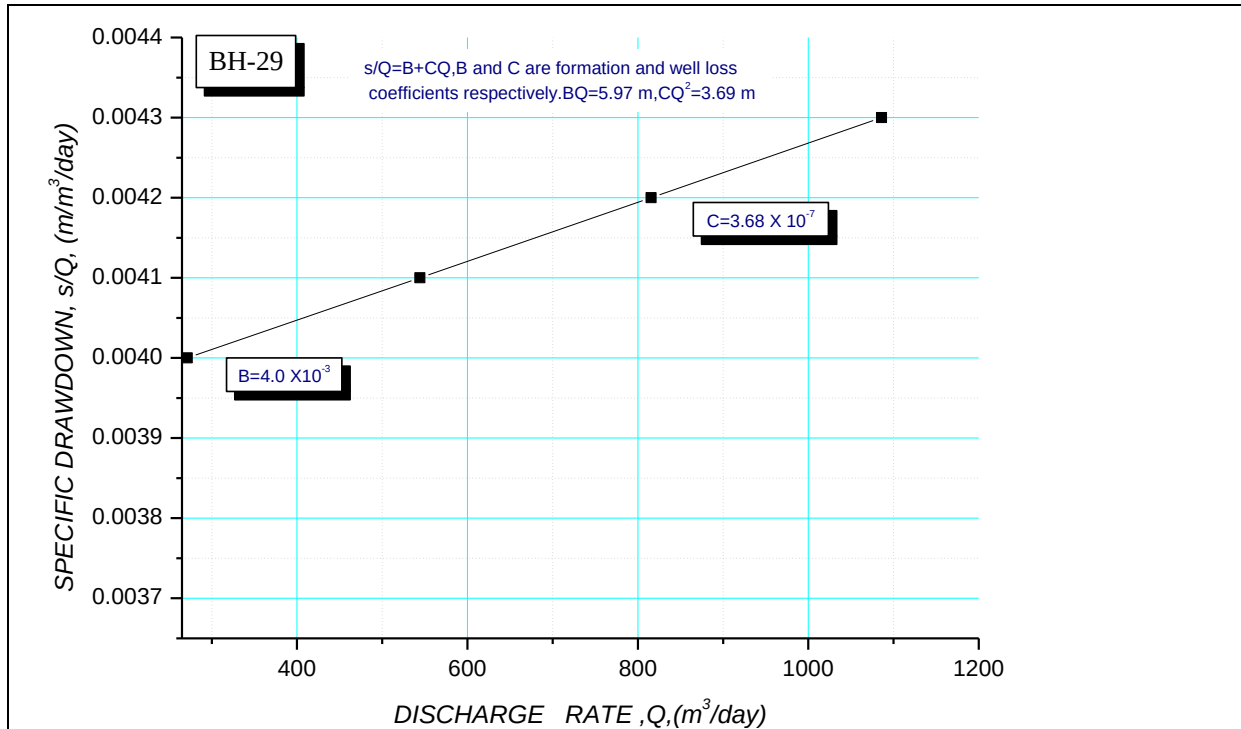


Fig. 4: Typical Specific Drawdown Curve for Borehole -BH 29

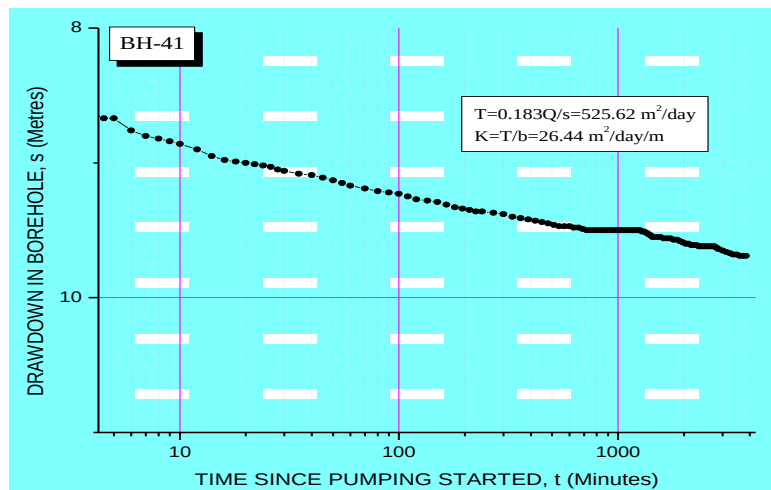


Fig. 5: Typical Constant-Discharge Rate Drawdown Curves showing Pumped Wells under Jacob's Model Response

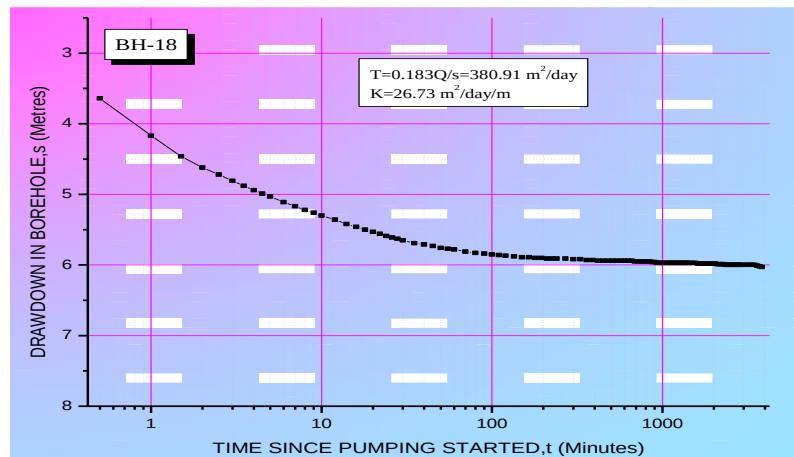


Fig. 6: Typical Constant-Discharge Rate Drawdown Curves showing Pumped Wells under a Recharge Condition

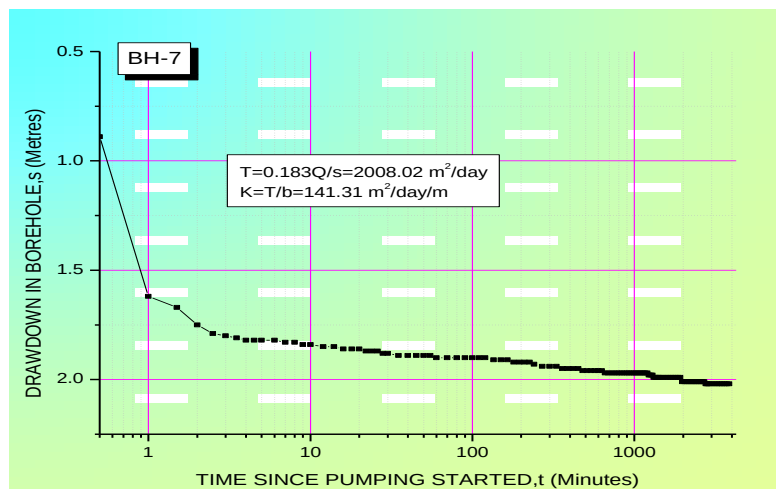


Fig. 7: Typical Constant-Discharge Rate Drawdown Curves showing Pumped Wells under Casing Storage/Steepening Effect

Fig. 6 represents typical time-drawdown curves for pumped wells operating under recharge conditions. The curves reflect departure from idealized conditions (Jacob's model response) in Fig. 5 above. The departure was the second legs that flattened or near horizontal. This reflection is diagnostic of a subsurface recharge tendency while the first leg of the curves is an indication of an enlarging cone of depression during the first 200 - 240 minutes of continuous pumping. During this period, the cone of depression does not extend to the river and no recharge was evident, but beyond, a source of recharge was encountered. The cone of depressions and the pumping level became stable. Thus, as the cone of depressions continued to enlarge, the flattening of the second legs or the horizontal part of the drawdown curves (at an increasing rate) became more significant. The second/horizontal legs not only a reflection of recharge but also, indicate an equilibrium condition where recharge equals well discharge after 200 or 240 minutes of continuous pumping. The class in Fig. 6 above is the most predominant of all the drawdown type-curves with 57.5% occurrence.

Fig. 7 typified the typical drawdown curves in which casing storage has altered the first or early part of the time-drawdown plots. They occurred next to the type-curves in Fig. 6 with 24.2 % of occurrence in the area. The first legs of the typical curves do not fit Jacob's modification or model response of the non-equilibrium theory (Schafer, 1978). The situation reflects the removal of water stored in the casing in the first few period of pumping before water begins to enter the well from the surrounding permeable formation. Only the second legs of the curves reflected the true behaviours of aquifers. These, therefore, remained the pumping test data that fit Jacob's model curve of the non-equilibrium theory (Cooper and Jacob, 1946) and not a reflection of a recharge tendency.

However, the values of the hydraulic parameters, specific capacity and associated hydrogeological considerations suggest well design practices with attendant minimum/sustainable drawdowns consistent with aquifer capacities and good groundwater prospecting. The entrance velocities of between 0.0048 - 0.0075 m/s obtained from the findings lie within the recommended value of not greater than 0.03 m/s (Driscoll, 1986; Roscoe, 1990). This provides a good measure of the effect of screen slot size on the yield.

It may therefore be concluded that the range of values of transmissivity, hydraulic conductivity, longer pumping and recharge source from the type-curves couple with other hydrogeological characteristic parameters determined from the production boreholes in the area sufficed that the area has the potential for high groundwater prospect/yields adequate for industrial, municipal, or irrigation purposes. This submission agrees with Driscoll (1986) aquifer transmissivity value of less than $12.4 \text{ m}^2/\text{day}$ for domestic wells or other low yield uses, and transmissivity value ($>12.4 \text{ m}^2/\text{day}$) for industrial, municipal, or irrigation purposes.

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